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Social Interactions, Emotion and Sleep: A Systematic Review and Research Agenda

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**SUMMARY**

Sleep and emotion are closely linked, however the effects of sleep on socio-emotional task performance have only recently been investigated. Sleep loss and insomnia have been found to affect emotional reactivity and social functioning, although results, taken together, are somewhat contradictory. Here we review this advancing literature, aiming to 1) systematically review the relevant literature on sleep and socio-emotional functioning, with reference to the extant literature on emotion and social interactions, 2) summarize results and outline ways in which emotion, social interactions, and sleep may interact, and 3) suggest key limitations and future directions for this field. From the reviewed literature, sleep deprivation is associated with diminished emotional expressivity and impaired emotion recognition, and this has particular relevance for social interactions. Sleep deprivation also increases emotional reactivity; results which are most apparent with neuro-imaging studies investigating amygdala activity and its prefrontal regulation. Evidence of emotional dysregulation in insomnia and poor sleep has also been reported. In general, limitations of this literature include how performance measures are linked to self-reports, and how results are linked to socio-emotional functioning. We conclude by suggesting some possible future directions for this field.

Abbreviations

AU – action units

DV – dependent variable

ECI – emotional context insensitivity

EMG – electromyography

EQ-I – emotional quotient inventory

ERP – event-related potential

fMRI – functional magnetic resonance imaging

HPA axis – hypothalamic–pituitary–adrenal axis

IV – independent variable

MSCEIT – Mayer-Salovey-Caruso emotional intelligence test

MSLT – multiple sleep latency test

NFR – nociceptive pain reflex

PSQI – Pittsburgh sleep quality index

REM sleep – rapid eye movement sleep

**INTRODUCTION**

Sleep is known to be important for health [1], and the health risks associated with sleep disruption include cancer, metabolic disorders, and cardiovascular illness [2]. The relevance of sleep to psychiatric disorders has also been established [3, 4]. Poor sleep quality and insomnia are pertinent to emotion, and previous studies have investigated the effects of loneliness, complicated grief, hostility, and impulsivity on sleep [5]. Sleep and emotion are closely linked, and the importance of this area has been increasingly recognized.

Recently, experimental paradigms with socio-emotional stimuli (i.e. emotional faces, voices, images, or movies) have been employed to investigate how sleep affects responses to stimuli. Emotion perception can therefore be defined as the sensory processing of emotional stimuli. Emotion is relevant to the meaning, or significance, which is given to events, and emotion, cognition, and motivation are interlinked [6]. Specifically, emotion can be associated with approach or withdrawal behavioral states, or motivational states of reward and punishment [7]. Affective states comprise a conscious emotional feeling, with associated autonomic, neuroendocrine, and somatomotor responses [8]. Emotional stimuli are therefore highly relevant for the well-being and survival of the perceiver [9].

Following the perception of a stimulus, the emotional significance to the perceiver is appraised [8]. This initial appraisal leads to an affective state and corresponding behavior [8], which is assumed to be proportionate to a situation [9]. Threatening stimuli can lead to the initiation of a behavioral response [9], with the initial appraisal contributing towards the resultant response. This correspondence of an affective response, behavior, and context, is disrupted in psychopathological conditions [10]. In particular, the conceptualization of an event is associated with an excessive or inappropriate emotional response [10]. This is due to a greater contribution of internal processes, such as idiosyncratic interpretations of an event [10].

[Please insert Figure 1.]

Emotion regulation also contributes towards emotion perception. Emotion regulation can be defined as the modification of an affective response by the recruitment of cognitive processes. Phillips et al. [8]

suggest that emotion regulation contributes towards the initial appraisal of stimuli, and to the affective state produced by stimuli appraisal. This implies that emotion regulation can affect the perception of emotional stimuli and the subsequent emotional state, suggesting two types of emotional regulation strategies. However, emotion is one of the most contentious areas within psychology [11], and the validity of distinguishing between emotion generation and emotion regulation is disputed [12]. The relationships between mood and emotional stimuli are therefore likely to be complex.

When the sleep of healthy subjects has been manipulated, evidence of increased emotional reactivity has been found, although evidence of emotional "blunting" has also been reported. Experimental tasks have also been used with poor sleepers, with a view to understanding the role of emotion in insomnia. However, results to date have raised some important questions, such as the directionality of emotion effects (i.e. emotional reactivity vs. emotional blunting), the concordance between different output measures (e.g. behavioral responses, physiological activity, brain responses), and the relative contributions of emotional functioning and social performance to results. A working definition of key terms is provided in Table 1.

[Please insert Table 1]

Furthermore, these issues have not been addressed in existing reviews. In general, reviews to date have summarized the literature on the bi-directional relationships of sleep and emotions, with a focus on self-reported measures of mood [13]. The literature on sleep stages, especially rapid eye movement (REM) sleep, and their role in emotional memory and associated affective experiences have also been reviewed [14, 15, 16]. However, a limitation of these reviews is that results from experimental tasks with socially-relevant stimuli or outcome measures are largely considered within an emotional context, rather than as measures of social functioning. This is relevant to the complex interactions between mood, emotional stimuli, facial expressions, and social interactions, and we aim to address these issues in this review.

Given the increasing use of objective measures to investigate the relationships between sleep and emotion, it seems timely to review the sleep/emotion field with reference to the existing literature on emotion and social interactions. Furthermore, integrating these areas seems necessary in order to aid the interpretation of results, and advance this area. In particular, we start by systematically reviewing the sleep and emotion literature, including sleep studies which have investigated emotion with

experimental tasks and/or objective outcome measures. We summarize results from these studies, placing results in the context of the relevant extant socio-emotional literature, and highlight some key methodological limitations. Lastly, we set out an agenda for future work in this area.

**SLEEP AND EMOTION PERCEPTION**

The effects of sleep on emotion perception have been increasingly studied, and we identified relevant papers in order to summarize this area which was done in two ways. Firstly, relevant papers were identified as published in an ongoing ad-hoc literature search. Secondly, relevant papers were identified via a systematic review of the literature. However, it should be noted that this systematic literature search was not linked to a quality rating of the papers, due to homogeneity in study designs and participants, dose of sleep deprivation, experimental tasks, and stimuli.

Papers were identified as indexed in PubMed (http://www.ncbi.nlm.nih.gov/pubmed/) via a search for the key terms relevant to sleep and emotion on 30$^{th}$ August 2014. The resultant 3293 items were then auto-filtered for article type, language, humans, and age. This resulted in 1716 items, and combined with those 33 papers previously identified resulted in 1735 unique papers.

[Please insert Figure 2]

We sought to identify those papers with an emotional task, and an associated neuroimaging, physiological, or behavioral dependent variable (DV). Emotional tasks were defined as those making use of socio-emotional stimuli as independent variables (IV), such as emotional words, images, or faces. Also included were papers with measures of emotional expressivity, perceived emotion in sleep-deprived or insomnia individuals, measures of emotional intelligence in conjunction with an objective DV, and tasks of emotional reactivity in memory paradigms. Emotional reactivity is defined in Table 1 as “unstable and rapidly changing emotions due to hyper-reactivity to emotional stimuli” [17].

These 1735 titles were then manually screened to identify those papers meeting the above criteria, and supplemented by an auto-search to identify and review those papers with “emotion” in the title. In total 72 papers were identified and their abstracts screened, with the full text paper screened where there was ambiguity. Papers with self-reported measures of emotion alone were not included.

Excluded were tasks of attentional bias (n = 2), stress paradigms (n = 4), memory tasks (n = 5), priming task (n = 1), and other stimuli (food stimuli n = 1; humor n = 1), studies based on self-reports (n = 17), reviews (n = 1), letters (n = 1), case studies (n = 1), non-insomnia patients (n = 2), and a circadian study (n = 1). The resulting 35 papers were then organized by the use of neuroimaging, physiological, or behavioral measures, as well as studies of emotional expressivity, emotional intelligence, and rapid eye movement (REM) sleep, and are summarized in Table 2.

[Please insert Table 2]

**EFFECTS OF SLEEP LOSS IN NORMAL SLEEPERS**

Firstly, we review evidence for effects of sleep deprivation and sleep restriction emotional responding. These studies of normal sleepers used neuroimaging, physiological and behavioral techniques. We then review those studies on emotional expressivity and emotional intelligence.

**Neuroimaging studies**

In 2007, Yoo et al. [18] reported that 35 hours of sleep deprivation increases amygdala reactivity to a series of increasingly aversive images. In particular, they report that sleep deprivation was associated with 60% greater magnitude of activation of the amygdala, and a three-fold greater extent of activation of the amygdala volume between groups. Similar results were found when the upper and lower quartiles of the stimuli set were compared, suggesting that amygdala reactivity to the baseline condition was not responsible for these results. Diminished amygdala-prefrontal connectivity was also found after sleep deprivation, suggesting a lack of cognitive control over emotional brain areas. However, there was greater connectivity within brainstem areas which are involved in autonomic activation. Behavioral responses (unpleasant/neutral) were also recorded to verify wakefulness. Although no significant group differences were found in the use of these labels, sleep deprived subjects tended to rate stimuli as more negative (p = 0.10).

The same group has also reported hyper-reactivity to *positive* stimuli following sleep deprivation. Gujar et al. [19] used a similar paradigm whereby increasingly arousing positive images were presented in an

emotional gradient. A night of sleep deprivation (32 hours) increased activation in brain areas responsible for reward, ~~such as the ventral tegmental area of the brain stem~~, as well as the amygdala and insula cortex between groups. ~~Specifically, sleep deprivation increased functional connectivity within regions of the left amygdala and left anterior temporal pole, and connectivity of the insular cortex with several regions of the visual cortex was increased relative to control subjects.~~ The bilateral amygdala showed increased reactivity, and decreased connectivity with the medial prefrontal cortex, bilateral orbitofrontal cortex, and left fusiform gyrus. The fusiform gyrus showed stronger connectivity with the left anterior temporal pole, and increased connectivity in the left superior insula and left lateral prefrontal cortex. There was also a significantly greater tendency of sleep deprived subjects to categorize stimuli as pleasant compared to neutral.

Using comparable tasks, Yoo et al. [18] and Gujar et al. [19] therefore report similar results with both negative-arousing and positive-arousing stimuli, i.e. increased emotional brain activation and decreased functional connectivity with cognitive control regions. The test times of these studies are also comparable, with both studies testing subjects at 5pm. However, the presentation of stimuli in an increasingly arousing gradient could affect results. In particular, this approach seems likely to conflate the initial perception of stimuli with the capacity to regulate subsequent emotion. Specifically, antecedent-based methods of emotional regulation affect the perception of the emotion-inducing stimuli, whereas response-based methods of emotional regulation target the subsequent emotional response [20]. Emotional regulation therefore contributes towards the appraisal of stimuli, as well as the subsequent emotional response and behavior [8]. Both studies report evidence of impaired emotional regulation via connectivity measures, and the intensity of an emotional experience could modulate its ability to be regulated [20].

Sleep deprivation has also been studied in conjunction with ~~a task of~~ emotional distracters, in a counterbalanced crossover study [21]. In this delayed matching to sample task ~~task subjects were first instructed to remember 3 faces. After a 10 second delay subjects were asked to judge whether a newly presented face was old or new. In the interim~~ emotional images of highly arousing negative images, low arousal neutral scenes, or visual control images were presented as distracters. Following 24 hours of sleep deprivation, performance ~~in this delayed-matching-to-sample task~~ was significantly impaired in comparison to rested wakefulness [21]. When functional magnetic resonance imaging (fMRI) results were analyzed, amygdala activation to emotional distracters following sleep deprivation was found to

correlate with working memory impairments. In particular, those with greater working memory impairments following sleep deprivation showed greater amygdala activation to emotionally distracting images [21]. The maintenance of performance was also positively associated with connectivity of the emotional brain and cognitive control areas. However functional connectivity between the amygdala and prefrontal cortices was impaired following sleep deprivation. Sleep deprivation was not found to affect behavioral ratings of emotional stimuli, with distractibility and emotional intensity assessed [21]. Importantly, this study suggests ways in which neural activation patterns and task performance are linked, indicating that increased amygdala reactivity to distracters and diminished prefrontal-amygdala connectivity correlates with working memory impairments. This could be relevant to increasing resilience to sleep deprivation.

The effects of 24 hours of sleep deprivation on the anticipation of emotional stimuli have also been studied in a within-subjects design [22]. In this task, a cue predictive of aversive or neutral images, or an ambiguous cue, was presented in advance of an emotional image. Sleep deprivation enhanced anticipatory brain activation to all predictive cues in the amygdala region, without emotion-specific effects. There was also a significant interaction of cue type with sleep deprivation in the right anterior insula, which showed greater activation to emotional cues than ambiguous cues [22]. Furthermore, trait anxiety was found to modulate these effects, with higher scores linked to greater amygdala activity. Identifying factors which increase vulnerability to sleep loss is important given the links of sleep and health [1, 2, 3, 4], and amygdala reactivity could contribute to this. These results by Goldstein et al. [22] appear broadly comparable to the effects of acute stress on amygdala activation [23]. In particular, acute stress induction increases amygdala activation to all images, reducing specificity and increasing sensitivity. Such effects of sleep deprivation on amygdala reactivity could contribute towards the development of psychiatric disorders. Specifically, sleep disruption has been found to increase the likelihood of psychiatric disorders developing following a traumatic event [24].

Emotional images have been used as stimuli in these four experiments. However other authors have used facial expressions of emotion in order to assess emotional responding. Facial stimuli are different from emotional images, in that facial expressions of emotion communicate information [25, 26] and serve social motives [27]. These different types of emotional stimuli - words, images, and faces - have been compared, with different effects found on the speed of processing, extent of neural activation, and induced emotion. Specifically, compared to faces, images are more complex and novel, and may be

more demanding to process, resulting in sustained patterns of activity [28]. Emotional images also induce greater experienced emotion than emotional faces [28]. However, brain responses to emotional faces are more pronounced in several brain areas [28]. Distinctive universal facial expressions have been identified for anger, fear, sad, enjoyment, and disgust, with weaker evidence found for other emotions [29]. In particular, anger/disgust and fear/surprise seem to be frequently confused, creating four emotional categories [30]. These "basic" emotions can themselves be further classified according to their associated levels of arousal and valence, in a dimensional approach to emotion [7, 31, 32]. The following studies in this section have made use of emotional face stimuli.

Cote et al. [33] measured the effects of sleep deprivation (31.5 hours of wakefulness) on emotion recognition, using behavioral measures in conjunction with event-related potentials (ERPs). When the behavioral response categorization labels were analyzed, sleep deprived subjects were significantly poorer at recognizing sad faces. These subjects were also slower to respond when the full emotional expressions were displayed. When images were morphed to vary the emotional intensity, sleep deprived subjects were less accurate at recognizing sad faces, and slower to recognize happy, sad, and angry faces. On the full-face task, sleep deprived subjects evidenced a smaller P1 amplitude and a larger N170 amplitude, with similar results found with morphed faces. At 50% morph level the P1 amplitude was also significantly smaller, and there was a significant three-way interaction for the N170 amplitude. These effects were linked to the increased perceptual difficulty of morphed faces, with a failure to make use of perceptual resources with subtle expressions of sadness. Neural reactivity increased for the threat-related emotions as they became more subtle. This suggests increased reactivity towards more ambiguous expressions with sleep loss, consistent with a behavioral study by Van Der Helm et al. [34].

The effects of sleep restriction on emotion has also been investigated, and evidence for emotional reactivity has been found with facial stimuli. In the paradigm of Motomura et al. [35], time in bed was restricted to four hours a day for five days. These authors report that sleep restriction increased emotional brain responses to negative face stimuli. Emotional faces showing happy, fearful, and neutral expressions were presented in two conditions. These stimuli were shown for 1000 ms in an "aware" condition, and 26 ms in an "unaware" condition, in a randomized crossover design. Significant differences in amygdala activation were found in the aware condition, when fearful and neutral faces were contrasted. This contrast was also associated with significantly impaired amygdala-anterior cingulate cortex connectivity [35]. When behavioral responses were analyzed, there were no significant

differences between groups in the responses or reaction times towards target images. However, button responses were used to verify wakefulness rather than to assess recognition performance. In general, decreasing stimuli presentation times of emotional faces impairs recognition [36], and it would be interesting to investigate how this paradigm is linked to behavioral recognition responses.

Also of interest would be the effects of different levels of sleep restriction and sleep deprivation on performance. In particular, there has been found to be a dose-response effect of sleep loss on measures of neurobehavioral functioning [37]. These authors report that cumulative sleep restriction results in performance impairments which are comparable to that of total sleep deprivation. Meerlo et al. [38] have also discussed the effects of sleep restriction with regards to markers of stress and arousal. They report that the adverse effects of chronically restricted and disrupted sleep can occur in two ways. Firstly, the effects of sleep deprivation on sympathetic and hypothalamic–pituitary–adrenal axis (HPA axis) activity could accumulate. Secondly, the chronic effects of this could be to dysregulate the stress and arousal systems, resulting in altered sensitivity and responses to stress. These changes become persistent via gradual changes on the stress systems and its regulation.

**Physiological studies**

Evidence of hyper-reactivity following sleep deprivation has also been found with physiological measures, specifically, there are greater pupillary responses to negative images when sleep deprived [39]. In this task, high arousal positive, high arousal negative and neutral images were selected, and presented in emotion blocks of 5 images. Each image was preceded by a 2 second warning cue, and presented for 6 seconds. Subjects were awake from 31-33 hours. There was greater anticipatory pupillary reactivity to negative stimuli following a night of sleep deprivation. Larger pupillary reactivity in the inter-stimulus interval following neutral trials was found with sleep deprivation too, along with effects while viewing negative images [40]. However, there were no significant effects on emotion ratings or reaction times with sleep deprivation [40]. This study supports the evidence for anticipatory reactivity following sleep deprivation reported by Goldstein et al. [22] on fMRI parameters. Moreover, behavioral results appear to be less sensitive to the effects of sleep deprivation, both in this study and Chuah et al. [21].

Measures of facial movements have been linked to a somewhat different pattern of results, and sleep loss slows intentional movements [41]. Schwarz et al. [41] asked subjects whose sleep opportunity had been partially restricted (sleeping between 2am and 6am) to “smile” or “frown” in response to emotional faces and scenes. Using electromyography (EMG) responses, they found that sleep deprived subjects were slower to respond. Dimberg suggests that the facial muscles involved in smiling and frowning respond congruently to emotional stimuli [42, 43, 44], although importantly these movements may not be visible by eye [44]. Modulating affective displays may, in turn, affect emotional experiences. In the facial feedback hypothesis, Izard [45] suggests that modulating expressed emotion affects the emotional experience itself. Facial muscle movements could therefore contribute towards both emotional experience and emotional regulation [45].

Furthermore, the relationships between different types of measures could be affected by sleep deprivation. Franzen et al. [46] examined how sleep deprivation affects the relationships between different measures, using the same sample as Franzen et al. [40]. In exploratory factor analyzes, they found that sleep deprivation influenced the relationships between subjective measures (such as self-reported mood and sleepiness) and objective measures (such as pupillography, and the multiple sleep latency test, or MSLT), making this distinction less clear [46]. This suggests that the relationships between the different components of emotions become dysregulated following sleep deprivation.

**Behavioral studies**

The effects of sleep deprivation on the ratings of emotional images have also been tested. Subjects were compared on their ratings of arousal and valence towards images depicting pleasant events, unpleasant events, and neutral. Images were presented in a random order for two seconds and rated after a one second pause. Behaviorally, a night of sleep deprivation was linked to more negatively valenced ratings of neutral images, with no effects on positive or negative stimuli when test and retest were compared [47]. This group difference was significant when mood was included as a covariate. Some evidence of effects with arousal ratings were also reported, with sleep deprived subjects rating unpleasant images more arousing than pleasant ones, an effect not found in control subjects [47]. This task appears comparable to that of Franzen et al. [40], although with discrepant results. In particular, Franzen et al. reported no effects with behavioral ratings.

One explanation may relate to the precise stimuli which were selected, and their associated normative ratings of valence and arousal. However, these ratings appear comparable (Tempesta et al. [47], pleasant valence: 8.0, arousal: 5.1; neutral stimuli arousal: 5.0, valence: 3.0; unpleasant valence: 2.0, arousal: 6.0; Franzen et al. [40] positive valence: 7.6, arousal: 5.3; neutral valence: 5.0, arousal: 3.3; negative valence: 2.3, arousal: 5.7). However, Franzen et al. collected behavioral ratings several hours after the eye-tracking task, and Tempesta et al. displayed stimuli on screen while response judgments were made. These differences may be relevant to the discrepant behavioral results between these two tasks. Also relevant could be that the images of Tempesta et al. were also presented in color whereas Franzen et al. used grayscale images. Additionally, the sleep deprivation period of Franzen et al. appears to be longer. Future studies should investigate the reasons for these discrepant behavioral results in greater depth. However, in general, behavioral studies appear to be less sensitive to the effects of sleep deprivation than neuroimaging or psychological studies.

Sleep deprived participants also show evidence of diminished inhibition and greater impulsivity to negative stimuli, in an emotional Go/NoGo task [48]. This task involves the presentation of neutral and emotional (positive and negative) words, which subjects are asked to respond to, or inhibit responses towards. Following 36 hours of sleep deprivation, subjects made fewer correct responses overall, with more incorrect responses to negative emotional stimuli. Sleep deprived subjects also responded more quickly (and incorrectly), to negative stimuli, suggesting a failure to inhibit responses to such stimuli [48]. When emotion words are compared to faces, emotion faces are processed faster, although with similar patterns of brain activity [49], suggesting that word stimuli are comparable to results with facial stimuli. However, it would be interesting to repeat this task using alternative stimuli and measures of impulsivity.

Facial stimuli have also been used to investigate the effects of sleep deprivation. Pallesen et al. [50] used schematic faces within a delayed matching-to-sample task. In this study of cadets, sleep deprivation was found to impair performance on accuracy and reaction times in the face-matching task. Dushenko and Sterman [51] have also investigated the effects of sleep loss, using a matching task with schematic faces. Following REM sleep deprivation, the recognition of these faces was found to improve in the left-hemisphere first presentation condition. Both of these studies were interested in hemispheric differences. In general task performance was impaired following sleep loss, and improved following REM sleep deprivation, although the emotion specificity of results was not reported. These studies indicate

that the nature of sleep deprivation affects results, with different sleep stages exerting different effects on performance.

In an emotion categorization task, Huck et al. [52] found no effects of sleep loss on simple emotion recognition, although complex emotion recognition was significantly affected. Stimulant medications were found to improve recognition of complex emotions following sleep deprivation. The emotion-specificity of these effects was not reported. In this experimental paradigm faces are presented until response, with the six emotional labels (anger, surprise, fear, sadness, happiness and disgust) presented on screen below the image. A similar task was employed in a complex emotion recognition task. Complex emotional faces were defined as those which are blends of two emotional faces, resulting in a ratio of two emotions which are displayed on the face. However, the extent to which such “complex” images are representative of how expressions are formed in real life is unclear. Different facial action units (AUs) may be displayed in different ways to represent emotional expressions [53]. The facial physiology is capable of displays of more than one emotional state at once, and emotion blends or sequences are commonplace [54]. This flexibility contributes to the ability to modulate facial expressions of emotion, depending on the situation [55]. Such emotional expressions may therefore be said to increase *perceptual* difficulty [33].

Also using face stimuli, Van Der Helm et al. [34] found reduced intensity ratings (in the mid-intensity range) following sleep deprivation, results which were driven by responses towards angry and happy faces. Subjective sleepiness was not found to correlate with results. In this task the stimuli were created by morphing expressions of anger, sadness, and happiness with the neutral image of a single male identity. The resultant ten blends, or morphs, were shown in emotional blocks in a randomized order. Participants were familiarized with the image sets prior to testing, and rated the perceived intensity of emotion. This was done on a four-point scale (definitely neutral, more neutral than emotional, more emotional than neutral, definitely neutral) following a two second image presentation.

Behavioral facial emotion recognition tasks typically involve the random presentation of the emotional expressions of several posers, with subjects asked to categorize the emotion shown using emotion labels. This is akin to real-life situations, where emotions are recognized from several options. Emotion recognition can also occur at high accuracy following a brief image presentation [36], and extended presentation durations (10 seconds) have been linked to results which fail to replicate under more

naturalistic presentation times [56]. Although emotion categorization and intensity responses are linked [57], the presentation of stimuli within emotion blocks could also have effects. For example, angry faces have been linked to sensitization responses within the hippocampus and other brain areas [58]. We suggest that sensitive tasks of emotion recognition performance could include categorization and intensity judgments, or the use of dynamic stimuli based on facial movements [53]. Alternatively, Adolphs [7] has suggested that intensity ratings could be made concurrently on several different emotional categorization options for each trial. Measures of accuracy could then be derived from these responses.

**Emotional expressivity**

While the previous studies have investigated the perception of emotion, other authors have been interested in how emotions are expressed. This is relevant to both social interactions and emotional regulation. Specifically, Minkel et al. [59] induced amusement or sadness via movie clips, and subjects' facial movements were visually recorded. Sleep deprived subjects were significantly less facially expressive when shown both types of movies compared to rested controls, with a larger effect size towards amusing clips than sad movies [56]. However, this study assessed overall expressivity of facial movements via the "FACES" scoring system. As such, the way in which sleep deprivation affects the specific components of emotional expressions is unknown. With regard to facial expressions as social signals, Ekman and Friesen [60] and Ekman, Friesen, and Tomkins [61], detail how different AUs combine to display the different emotional expressions. How facial expressivity was linked to expressed emotion in this study is therefore unclear, although the precise links of facial expressions to emotional experiences is subject to debate.

Ekman [62] suggests that some emotions have no distinct expression, and that subjective affect may not correspond to facially expressed emotion. This indicates that the processes involved in emotional experience and emotion expressions are separable. Emotional expressions serve social motives [27], and the "readout" hypothesis suggests that motivational-emotional processes with social implications are displayed on the face [60]. Furthermore, Blair [25] stresses the role of expressions in communication, with an audience important to emotion displays. Ekman and Friesen [54] have described four display rules, which can serve to de-intensify, over-intensify, appear neutral, and mask experienced emotion, and these are subject to social norms and context. Such modulations of affective displays may, in turn,

affect emotional experiences [45]. Expressing fear alters parameters (e.g. faster eye movements, increased nasal volume) which are linked to behavioral action tendencies [63]. Future studies in this area should consider reporting the social context of testing (e.g. solitary, group testing, or experimenter present), and this would be interesting to investigate further. Furthermore, the environment has been identified as a fourth component of emotional instability [64] (see Table 1).

Individual differences in emotional expressivity could also be relevant. People vary in their emotional expressivity, and this relates to differences in the specificity of expressions, the threshold for expressions, and aspects of the timing of expressions [62]. Furthermore, there are differences between people in the structure and differentiation of facial muscles, and in the neural control of them [65]. The ability and tendency to produce universal facial expressions also varies between people [65]. Such differences have been observed experimentally. In 1924, Landis [66] conducted a series of experiments whereby the facial expressions produced by emotion-inducing stimuli were recorded, and noted two factors of emotional disruption. One was related to the tendency to display emotion, and the other was the emotional stability, or duration of emotional impact, following an emotional upset. As such, individuals have been found to respond in idiosyncratic ways to emotion-inducing procedures, with different patterns of facial expressions observed between individuals [66]. Future studies could consider how facial reactivity relates to measures of emotion, and how sleep affects this.

Sleep deprivation also affects vocal expressivity [67]. Following a night of sleep deprivation, subjects use fewer words, and are judged to express less positive affect and more negative affect via speech. The acoustic properties of speech are also affected by sleep deprivation, with effects on several parameters [67]. Of 30 acoustic properties studied, there was significant disruption to several properties (e.g. ~~as a decreased rate in F0~~, increased jitter~~, decreased psycho-acoustical bark at specific high frequency energy band, increased shimmer,~~ decreased pauses and decreased high frequency energy). In an earlier study, Harrison and Horne [68] have reported effects of sleep deprivation on speech. These authors found that sleep deprivation decreased word count on trial 3, with decreased nouns and adjectives on this trial. Sleep deprived subjects also generated a larger proportion of semantically related words at trials 2 and 3. In addition, intonation was found to be affected by sleep deprivation, and was more inappropriate, with voices reported to be more monotonic or flat. There was a corresponding increase in ratings of fatigue.

Taken together these results suggest that speech is affected by sleep deprivation, and that perceivers detect these differences on several measures. Specific parameter differences can also be detected by computerized analysis. Given the importance of vocal expressivity to social interactions, it might be worth investigating how perceivers interact with sleep deprived individuals. The emotional reactions of observers to such expressions might also be worth investigating. This would seem to be relevant to both facial and vocal cues. Axelsson et al. [69] have found that *facial* cues of sleep deprivation are detected by observers, with such images rated as being less healthy and attractive. The social implications of sleep loss are therefore worth investigating in terms of the effects on the perceiver. Also relevant is the concordance between measures of timing and maximum expressivity in a social exchange. This might be relevant to individuals with insomnia disorder [70], who are thought to have difficulties with emotion regulation [73], and there is evidence that voices can be "fatigue-proofed" [71].

Furthermore, individuals who have been sleep deprived are perceived to be more sad and fatigued, with significant differences in facial cues [72]. These specific facial cues included redder eyes, hanging eyelids, swollen eyes, darker circles under the eyes, pale skin, more wrinkles/fine lines around the eyes, and more droopy corners of the mouth. This is from images being taken of unexpressive, or "neutral" faces following 31 hours of sleep deprivation and 5 hours of sleep. Sadness ratings and ratings of fatigue were found to be correlated. Such studies suggest that sleep loss affects appearances and that this can be detected by observers. Future studies might wish to consider the role of familiarity in how faces are assessed. This could also be relevant to insomnia disorder subjects in whom social interactions are an area of concern [70], and sensitivity to these changes may contribute towards the maintenance of insomnia disorder [73].

**Emotional intelligence**

Emotional intelligence could also modulate reactions to sleep loss. Killgore [74] assessed emotional intelligence, measured subjectively (via the emotional quotient inventory, or EQ-i) and objectively (via the Mayer-Salovey-Caruso emotional intelligence test, or MSCEIT). Subjects reporting < 6.5 hours of sleep the previous night scored significantly lower on subjective emotional intelligence than those subjects who reported > 8 hours of sleep the previous night, with no significant group differences on objectively measured performance. Insomnia complaints were not found to account for the correlation of total sleep time with subjective emotional intelligence. When resting-state fMRI results were

analyzed, greater negative functional connectivity was found between the right ventro-medial prefronal cortex and right amygdala, and this was negatively correlated with greater reported total sleep time. The strength of this connectivity correlated with overall subjective emotional intelligence, but effects with objective emotional intelligence were not significant. Furthermore, insomnia complaints appear to account for the correlations between emotional intelligence and functional connectivity [74]. Of particular interest is the failure to find deficits in objective performance, although there were significant effects on subjective and neuroimaging measures.

In a new approach from the same group, Weber et al. [75] calculated sleep credit as the difference between habitual sleep time, and the reported minimum amount of sleep necessary before impairments became apparent in ability to work. ~~In the right middle orbitofrontal gyrus and the left gyrus rectus/superior and medial orbitofrontal gyrus, greater grey matter volume was associated with habitual “sleep credit”.~~ Total EQ-i scores were found to correlate with the left gyrus rectus and the superior and medial orbitofrontal gyrus. Volume of this area correlated with interpersonal subscale of the EQ-i. Impairments in subjective emotional intelligence following sleep deprivation have also been previously reported by this group [76]. Taken together these results suggest significant effects of sleep on subjective emotional intelligence and brain responses, but not on objective measures of emotional intelligence.

**ROLE OF (REM) SLEEP IN EMOTIONAL REACTIVITY**

There is much evidence that sleep benefits the memory of emotional content, and it has been suggested that REM-sleep plays a role in maintaining an emotional memory, while removing its associated emotionality, or “affective tone” [77]. We now briefly review the evidence for how sleep affects emotional *reactivity*.

Baran et al. [78] report evidence of attenuated arousal and valence ratings of negative emotional images following wakefulness, in contrast to sleep. This effect was associated with greater time in REM sleep. Evidence of more rapid extinction of fear responses have also been reported by Kuriyama, Soshi, and Kim [79]. These authors used movie clips of vehicle accidents or safe driving as stimuli. They report that there were significant differences between sleep and wake groups on the fear ratings of “safe” movies on day three, with lower ratings following sleep deprivation. Sleep deprivation was also associated with

a diminished skin conductance response (SCR) to incorrectly identified stimuli in all contexts. However, Van Der Helm et al. [80] report decreased intense emotional ratings, and increased non-emotional ratings with sleep, with no such effects found in wakefulness. This result was associated with REM sleep. As such the evidence as to how sleep affects emotional *reactivity* is currently unclear, and further work is needed to clarify this issue, and the role of specific sleep stages and especially REM sleep.

Another approach has been to assess emotional ratings comparing old-new images, with early or late sleep periods. Wagner, Fischer, and Born [81] found late, REM-rich sleep to enhance old-new valence ratings of images towards more negative ratings, compared to early sleep and wakefulness. The early sleep condition took place for three hours from around 23:00 to 02:00, and had significantly greater slow-wave sleep than late sleep. Late sleep took place from 03:00 to 06:00, with significantly greater REM sleep. An additional experiment found similar effects with a full night of sleep. Significant differences were found between these sleep conditions on the emotion ratings of images before and after sleep (i.e. emotional habituation/sensitization). Images were rated more positively after early sleep and more negatively after late sleep, with no such effects on arousal ratings [81].

Emotional ratings of old-new images have also been studied in conjunction with partial sleep deprivation. Emotional adaptation has been investigated via REM sleep deprivation [82]. Lara-Carrasco et al. found REM sleep deprivation to be linked to greater emotional adaptation towards images, on subjective ratings of arousal. These results suggest that emotional adaptation/habituation is not benefited by REM sleep [81, 82]. Partial sleep deprivation has also been investigated with other tasks. Rosales-Lagarde et al. [83] report that REM sleep deprivation enhances brain reactivity to emotion, in a task whereby participants were asked to imagine themselves within an emotional scene shown on screen. These results indicate the need for further research to clarify the role of REM sleep in emotional reactivity. However, REM-sleep deprivation paradigms may produce results which are difficult to translate to everyday life. In this regard we prefer the early/late sleep deprivation paradigm of Wagner, Fischer and Born [81].

Nap paradigms have also been used to investigate emotional responding. Gujar et al. [84] report a role of REM sleep in diminishing emotional reactivity following a nap, when subjects are asked to rate the emotional intensity of a face displaying varied emotional intensities, shown in emotion blocks (anger, fear, happy, sadness). In this task, participants who did not nap showed increased reactivity to these

emotional expressions, which was reversed by napping and in particular by REM sleep. Napping could also aid habituation towards emotional images when physiological reactivity is assessed [85]. Pace-Schott et al. used negative and neutral images, and assessed responses towards repeated and novel image sets. These authors report evidence of habituation (skin conductance response) in the nap group to repeated stimuli, a result which was not found in wake group. This was found for negative stimuli. There was also significant inter-session habituation in the wake group, but not the nap group, on heart-rate deceleration and corrugator electromyogram (EMG) responses. EMG responses in the wake group were found to sensitize, and these results were found for both negative and neutral stimuli. In general, results suggest a role of REM sleep in emotional responding. However the precise role of REM sleep in emotional reactivity clearly warrants future attention.

## EFFECTS OF POOR SLEEP QUALITY & INSOMNIA

In the following section, we describe those studies which have investigated the links of poor sleep quality and insomnia with socio-emotional functioning. All insomnia subjects were tested outside of the context of any treatment study.

### Neuroimaging studies

Prather, Bogdan and Hariri [86] used the Pittsburgh sleep quality index (PSQI) [87] to obtain a subjective evaluation of sleep quality, and investigated its links with brain activity. This was done via a matching task with emotion faces; a task previously found to engage the amygdala. They found that poor sleepers, defined on the basis of PSQI scores, showed significant relationships of amygdala activity with measures of psychopathology (depression, stress, and anxiety). These results were not found in normal sleepers. Such results add support to the relationships of sleep and mental health [3, 4], and suggest that poor sleep quality affects the relationships of brain activity with indicators of psychological distress. Franzen et al. [46] have previously found sleep deprivation to alter the relationships between various subjective and objective measures of sleep and emotion, and the process by which emotional dysregulation occurs could be different in normal sleepers and poor sleepers. Interestingly, the precise task demands can affect how stimuli are processed. In particular, selecting emotion labels has been described as a cognitive task, with evidence of top-down effects on the emotional brain, whereas matching faces has

been described as perceptual [88, 89]. Such tasks could be useful in order to assess emotional regulation and sleep.

Another type of paradigm is to investigate emotion regulation strategies by asking participants to regulate their reactions to emotional information. Minkel et al. [90] asked subjects to view negative or neutral emotional images, and to either maintain attention, or to use cognitive reappraisal to reduce their emotional reaction. In a sample drawn from the general population, subjective sleep quality, as measured by the PSQI, was not found to be associated with amygdala activation during emotion regulation. However, the use of sleep medication was associated with less activation in a medial prefrontal cortex area, with no effects of other PSQI subcomponents. Future studies might wish to employ this paradigm with normal sleepers and varying levels of sleep deprivation, in order to assess changes in the processes by which emotional regulation occurs.

Baglioni et al. [91] have also recently studied the effects of sleep-related and emotional stimuli on amygdala activity in insomnia disorder. These authors report that at the first presentation of stimuli, healthy controls show increased amygdala activation to negative stimuli compared to neutral stimuli with similar arousal levels. There were no such differences in insomnia disorder. When insomnia-relevant stimuli were shown, insomnia subjects showed increased amygdala activation to disorder-related stimuli compared to the non-insomnia stimuli. The opposite pattern was found in healthy controls. When neutral moderate, negative moderate and sleep-related negative stimuli were presented to healthy good sleepers, the amygdala activation levels were comparable between the first and second presentations. However, insomnia participants showed increased amygdala activation levels at the second presentation of neutral moderate images. These subjects also showed less amygdala activation at the second presentation of negative moderate and sleep-related stimuli.

**Physiological studies**

Emotional reactions have also been investigated in insomnia participants with multiple measures of emotion. Baglioni et al. [92] presented subjects with positive sleep, negative sleep, positive, negative, and neutral images, and measured their responses using physiological measures (EMG, cardiac vagal tone and heart-rate) and behavioral ratings. These authors report evidence for emotional reactivity in a group of primary insomnia subjects. People with insomnia showed decreased tonic activity of the

corrugator muscles in response to sleep-positive stimuli, unlike controls. There was also evidence of increased tonic activity of the zygomatic muscle to all stimuli in those with insomnia. Cardiac vagal tone was also increased to all stimuli in insomnia. The valence ratings of negative and negative sleep-related images in insomnia were not significantly different, unlike controls. Similar results were found with arousal ratings, and negative sleep-related stimuli were rated as more arousing than positive sleep-related stimuli, which was also unlike controls.

These results suggest that in insomnia there was less activation of the “frowning” muscles to positive sleep-related stimuli, and increased activation of the “smiling” muscles to all stimuli. Insomnia participants rated sleep-related negative stimuli and negative stimuli similarly on valence, and rated positive sleep-related stimuli as less arousing than negative sleep-related stimuli. All stimuli were linked to increased cardiac vagal tone in insomnia subjects. These results may be interpreted in terms of an increased negative emotional reaction to positive sleep-related emotional stimuli in normal sleepers, and similar arousal ratings of sleep positive and sleep negative stimuli. Normal sleepers also evidenced less positive emotional responses to all five emotional image categories. The valence ratings of negative and sleep-negative stimuli were significantly different in normal sleepers. Normal sleepers also responded with decreased cardiac vagal tone to all stimuli, unlike insomnia subjects. These results suggest systematic differences between normal sleepers and insomnia subjects across multiple levels of responsivity: subjective, cardiac, and EMG.

A second study has also investigated emotional responses in insomnia, via physiological measures. Evidence of lowered subjective ratings of valence was found in response to emotional images in insomnia participants, who also showed evidence of impaired ability to regulate emotion [93]. Specifically, participants were shown images of mutilation, erotica, or neutral images, and their emotional reactions were assessed via behavioral ratings and physiological measures. The relationships between pain ratings and a physiological measure of the pain response (nociceptive pain reflex, or NFR) were diminished in insomnia subjects. Insomnia appears to disrupt the relationships between physiological measures, subjective measures, and responses to stimuli. Future studies might wish to consider the point at which these relationships become dysregulated as insomnia disorder develops.

**Behavioral studies**

There is also recent evidence that insomnia affects the subjective ratings of emotional stimuli. Kyle et al. [94], using emotional face stimuli, found evidence that the subjective intensity ratings of fear and sadness were blunted in insomnia subjects. The categorization judgments of angry, sad, happy, and fearful faces were unaffected. In this study emotional faces were presented in a random order, and displayed until response. Emotional intensity judgments were not found to correlate with sleep diary responses, measures of sleepiness, or daytime functioning. However, there were significant negative associations of intensity judgments with anxiety and depression scores in insomnia subjects. In these subjects anxiety correlated negatively with anger, happiness and overall judgments. Overall intensity judgments and sadness ratings were negatively correlated in this group. In healthy controls, sadness ratings were linked to anxiety. As such the perception of emotion from faces appears to become linked to psychological distress, whereas normal sleepers fail to show such a pattern. This could be relevant to the results of Kyle, Espie and Morgan [70], who found that insomnia subjects reported concerns regarding social interactions.

**SUMMARY**

Results from neuroimaging studies suggest that sleep loss affects the processing of emotion, with similar effects found with positive [19] and negative [18] stimuli. These results are suggestive of both increased reactivity, and altered connectivity. Sleep loss also seems to amplify anticipatory activity, towards all cues [22] or when expecting negative emotional stimuli [40], and this discrepancy could depend on the measure of emotion (fMRI/pupillography) and/or task. Similar neural effects of sleep deprivation are reported by Chuah et al. [21]. These authors report that increased emotional distraction with sleep deprivation is linked to impaired prefrontal-amygdala connectivity. These results could be in keeping with behavioral evidence of impaired inhibition following sleep deprivation [48]. Furthermore, emotional images could be associated with greater subjective emotion and more sustained neural processing, suggesting sustained patterns of activity [28]. However, an important issue with these neuroimaging studies relates to the relative nature of the reported results. In particular, results are contrasted relative to another condition or resting state activity, and as such, the responses to the initial condition could result in the appearance of positive or negative results. However, results appear consistent with regard to effects of sleep deprivation on neural activity, across different types and durations of sleep loss.

The effects of sleep loss on behavioral ratings are less consistent. With emotional images, Chuah et al. [21] and Franzen et al. [40] found no effects of sleep deprivation on emotional ratings, although effects have been reported by Tempesta et al. [47] on *neutral* images. Yoo et al. [18] and Gujar et al. [19] also report evidence of effects on emotional ratings with sleep deprivation. The reasons for these discrepant results appear unclear, although possible explanations may be related to the images presented, features of their presentation, or the rating scale which was employed. Also relevant could be characteristics of the participant group. Working memory [22] and trait anxiety [23] have both been identified as factors which modify the effects of sleep loss on neural responses. Future studies should investigate the reasons for these different reactions to emotional images in greater depth.

With emotional faces, Huck et al. [52] reported no effects on basic emotion recognition, and Motomura et al. [35] found no effects with button responses to target stimuli. However, Huck et al. [52] reported effects of sleep loss on complex emotion recognition, and Van Der Helm et al. [34] found impairments in intensity ratings of subtle, mid-intensity ambiguous, emotional images. Pallesen et al. [50] also reported lower accuracy and increased reaction times, in a matching task with schematic images. Using schematic images, Dushenko and Sterman [51] also found impaired facial recognition performance. However, neither of these two studies or Huck et al. [52] reported effects on specific emotions. Sleep loss seems to impair the processing of emotion from faces, and this effect seems most apparent with more complex tasks. Different cognitive processes could also be involved in these different tasks. Specifically, perceptual processes could be more involved in face matching, whereas cognitive processes could be more involved in emotional labeling, a task which has also been linked to emotional regulation processes [88, 89]. Emotional intensity ratings have also been studied less, and may follow on from categorization decisions [57]. We suggest that future studies should focus on identifying sensitive and ecologically valid tasks of facial emotion recognition, taking account of the social implications of such tasks.

Evidence of impaired performance on emotional face tasks appears consistent with studies of expressed emotion, and with self-reported decreases in emotional intelligence and interpersonal functioning following sleep deprivation [46]. Minkel et al. [59] found that sleep deprived subjects were less facially expressive in response to emotional stimuli, and Schwarz et al. [41] found evidence of slower facial responses with sleep loss. Similarly, McGlinchey et al. [67] report that sleep deprived subjects were less vocally expressive, with similar results reported by Harrison and Horne [68]. These results seem

consistent with reports of impaired subjective emotional intelligence following sleep loss [76]. However, objective measures of emotional intelligence have been found not to be affected by sleep loss, despite significant effects on subjective emotional intelligence and neural reactivity [74]. As such, sleep loss seems to impair performance on tasks related to social functioning, on subjective measures, performance measures, and expressivity measures. Importantly, these tasks could also be tapping in to emotional processes. The relationships of emotion generation with emotional regulation are disputed [11, 12], and expressivity could both be a consequence of emotion [39, 44], and contribute towards emotional regulation [44, 45]. Separating these processes out appears particularly relevant for insomnia disorder, due to its links with emotion regulation [73].

With regard to insomnia, there is evidence of impaired emotional regulation [93], and increased emotional responsiveness [92], when multiple physiological measures are assessed. With socially-relevant stimuli, however, insomnia subjects make lower ratings of intensity in faces [94], with comparable results with emotional images [93]. Evidence of altered brain activity has also been reported in conjunction with sleeping medication use and emotional regulation [90]. In poor sleepers, the relationships of amygdala activity with measures of psychopathology are also disrupted [86], with similar results recently reported in insomnia disorder [91]. Future studies should consider the trajectory of how emotional reactivity is altered across different phases of insomnia disorder (e.g. predisposing factors, acute, and chronic insomnia) and with different comorbidities.

## LIMITATIONS

### Task characteristics & demands

The studies of Yoo et al. [18] and Gujar et al. [19] have displayed stimuli in an increasingly emotional gradient, based on normative data, and this may exaggerate the effects of sleep deprivation. In particular, such a presentation would be expected to prohibit any return to an emotional baseline [66], which could itself be negatively affected by sleep loss. This could lead to more extreme emotional states which are increasingly difficult to regulate [20], and makes it difficult to specify whether the processes involved in emotion generation or emotion regulation are contributing towards results.

While the relationships between these processes are complex and debated [12], it seems important to attempt to identify the stage(s) at which sleep deprivation affects emotions. Different task instructions could be used to assess this. Emotional labeling could engage cognitive processes, whereas a matching task may involve perceptual processes [89], and subjects have been asked to modulate their emotional reactions via specific regulatory strategies [90].

A further limitation may relate to the way in which facial stimuli are created. Ekman and Friesen [60] have identified facial action units which are responsible for expressing an emotion, and physiological constraints are important to how expressions are formed and displayed in real life [7, 54]. Importantly, such faces could increase perceptual difficulty [33]. Landis [66] suggests the importance of distinguishing between emotional expressions and social expressions, and the social context in which testing took place could also be relevant to emotional expressivity [95].

**Social effects**

The socio-communicative role of emotion is important, and this modulates the expression of emotional displays [39, 54]. Emotion perception involves stimulus appraisal, emotion regulation, and affective states [8], and these brain systems overlap with those involved in face processing [7]. The social relevance of tasks is therefore important to consider, and this seems especially important when expressivity is assessed, or when socially-relevant stimuli are used. Furthermore, the correspondence between self-reported mood and emotional task performance, and their associated neurological and physiological correlates, are likely complex. Indeed, the relationships between objective and subjective measures of emotion may be affected by sleep deprivation [46], suggesting benefits of assessing subjects using multiple measurements, and the importance of the social context.

In support of this, altered perception of facial emotions is reported in insomnia and with sleep deprivation [34, 94]. Sleep loss is known to alter the stress system [38], and insomnia has been associated with hyperarousal [96, 97]. As such, evidence of hypervigilance or improved performance may be anticipated, although expressed emotion is also reportedly “blunted” with sleep loss [59, 67] with slower facial movements [8]. The relationships between emotion perception, emotional expressivity, and emotional experiences also seem to be important to investigate further. For example, Kyle et al. [94] reported differences between normal sleepers and insomnia participants on the

associations between emotional intensity ratings and psychological distress. This could occur as a result of the chronic effects of sleep loss [38] or pre-existing differences in emotions between groups.

## FUTURE DIRECTIONS

Four avenues of future research seem most pertinent, related to 1) diverse measures of emotional functioning, 2) multi-faceted tests of social functioning, 3) role of sleep stages and circadian effects, and 4) inter-individual vulnerabilities of sleep and emotion.

### Diverse measures of emotional functioning

*Measured emotion*

Emotion is complex, and single measures may provide an incomplete picture of emotional functioning. Self-reported measures can be used to indicate subjective emotion; behavioral tasks can be used to assess objective performance; and physiological and neuro-imaging measures can provide information as to the neural, physiological and temporal mechanisms of emotional processing and experience (see Table 3.). The inter-relationships of these measures could also be complex, and this is affected by sleep loss [46]. Furthermore, emotional processing could itself comprise several components, and differences may emerge at different stages. Emotion seems to comprise several elements, such as reactivity to emotion, the duration of emotional impact, and tendency to express emotion [66]. To investigate these, experimental tasks could include manipulating the stimulus presentation time and inter-stimulus interval, as well as investigating the effects of feedback on performance and anticipatory effects, and subjective performance. The relationships between different types of measures also appear to be important to consider.

[Please insert Table 3.]

*Emotional context*

The emotional context of facial expressions also affects their processing [98, 99] and there is evidence that state anxiety is associated with a greater use of contextual cues [100]. As such, the situational

context could exert additional effects on emotional processing following sleep loss. Furthermore, mood is thought to become more independent of the situation with increasing illness severity [10], and sleep could contribute to this [24]. The contribution of context to emotion has been investigated in depression, and insomnia and depression are linked [4]. Blysma, Morris and Rottenberg [101] have performed a meta-analysis of emotional reactivity (emotional context insensitivity; ECI) in major depressive disorder, finding that depressed individuals show diminished responses to both positive and negatively valenced stimuli. This was discussed as insensitivity towards the emotional context within this disorder. Beck [10] has previously discussed the correspondence between a situation and mood states relevant to psychological disorders, suggesting a greater role of internal cognitive processes with psychological disorders. The precise context of an experiment is also important to consider when investigating socio-emotional functioning, although this may become less relevant with specific patient groups such as major depressive disorder [101].

**Multi-faceted tests of social functioning**

*Social "building blocks"*

Social functioning is complex, and several processes contribute towards socially-competent behavior [102]. Specifically, social interactions involve the comprehension of social cues, such as expressed behavior and speech, in conjunction with knowledge about a person and situation. Gaze [103, 104]**,** body cues [105], and voices [106] are all relevant social signals. These different signals influence each other, and emotional faces showing direct gaze are processed less efficiently [104]. The way in which this integration occurs can be affected by individual factors, such as anxiety [103]. Social competence includes face recognition as well as emotion recognition [102], and the changeable aspects of a face (such as movements) and its invariant aspects (e.g. identity) are both important to face perception [107], and contribute towards the social context.

Related to this, information about an individual's identity is thought to be somewhat independent of emotion [108, 109]. Importantly, "neutral" faces are arguably not unemotional. In particular, unexpressive faces are judged on two dimensions, namely dominance, and trustworthiness or valence, and these are linked to trait judgments [110]. Familiarity of faces also affects the perception of emotion [111], and familiar and unfamiliar faces seem to be recognized qualitatively differently [112]. Such basic

sensory/perceptual, cognitive, and emotional processes are thought to lead to the development of the higher-order capabilities which are involved in social functioning [102] – for example, emotional contagion is a pre-requisite of empathy [113]. As such, future research aimed at these “building blocks” could help to identify the point at which emotional impairments appear.

*Empathy & social interactions*

Importantly, emotional behavior can serve social motives [39], and reflect emotional states [31]. Such social motives may contribute towards the additional processes that are involved in social competence, such as theory of mind [102], which has also been called cognitive empathy [114]. Theory of mind, or “mentalizing”, is a form of meta-cognition [115], and is thought to be an explicit process [116, 117] which engages the neural systems involved in self-projection [118]. Implicit processes which are involved in social cognition include prejudice and perspective taking (i.e. tracking the mental states of others). Such processes are relevant to social emotions, like compassion and embarrassment, and social decision making, which includes fairness, trust, and Schadenfreude [118]. Indeed, performance on social decision-making tasks has been found to be affected by sleep deprivation [119, 120, 121].

Context also contributes towards social behavior, and adaptive socially competent behavior is the result of the match between genotype and the environment [102]. The social environment might mitigate the effects of sleep loss. Trait factors such as extraversion-introversion, in interaction with the social context, have been linked to altered performance following sleep deprivation [122]. It is also important to consider the effect of sleep loss on dynamic social exchanges. For example, people who have been sleep deprived are judged to look less healthy and attractive [69], and such trait judgments correlate with perceived trustworthiness [123]. As such, sleep loss could affect the sleep-deprived person‘s ability to interpret social information. It could also affect the perceptions made of the sleep deprived person, and behavior towards them. Such factors may be important in the development of insomnia disorder.

**Sleep stages & circadian effects**

*Sleep stages*

The role of specific sleep stages, especially REM sleep, in emotional reactivity is of particular interest, and this sleep stage has been implicated in psychiatric disorders [15, 124], such as depression [15, 77]. The "sleep to remember, sleep to forget" hypothesis posits that with sleep an emotional memory is strengthened while its associated emotional effects are weakened, and REM sleep is crucial to this [77]. This process is thought to ameliorate any hyperarousal, and its disruption may contribute towards depression and post-traumatic stress disorder [77]. However, studies on how sleep relates to emotionality appear contradictory. Discrepancies in methods relating to sleep (early/late sleep restriction, REM sleep deprivation and restriction, nap paradigms), emotion (e.g. adaptation, old/new contrasts), and measurements (valence and arousal ratings, experimental tasks, neuroimaging, physiological) likely contribute towards these effects. Studies with combined methods and measures would help to clarify the role of REM sleep in emotional reactivity, as would studies investigating changes in emotionality over time, as well as the role of the different sleep phases.

*Circadian effects*

Few studies have investigated the role of circadian processes on emotional tasks. While sleep loss and sleep disruption have been found to affect emotion perception, the circadian system could also exert effects. Five studies, to our knowledge, have looked at how the circadian system affects emotionality in healthy subjects using objective measures of emotion. Circadian effects have been investigated via measures of diurnal preference, with Paradee et al. [125] reporting a significant effect of chronotype-congruent test times in overall emotion recognition performance among a group of rehabilitation patients. Other researchers have investigated the role of light in emotion perception, and blue light, which plays an important role in the circadian system, has been found to affect how emotional information is processed [126].

In another approach, emotionality has been assessed at different times of day. Hot, Leconte and Sequeira [127], presented subjects with images of neutral scenes and high arousal negatively-valenced scenes, and recorded the skin conductance response. In a within-subjects design with seven different test times, at 2-hour intervals between 09:00 and 21:30, they found a time of day effect on the skin conductance response to aversive images. Specifically, they found a significant linear trend to unpleasant images, and a significant quadratic trend to neutral images, across the day. Hasler et al. [128] have also investigated how emotional behavior varies across the day via the sampling of ambient noise.

These authors report a significant diurnal effect on behaviors associated with positive affect, namely socializing, laughing, and singing. No such effects were found with arguing or sighing, suggesting that behaviors linked to negative emotion show no diurnal patterns. Similarly, Golder and Macy [129], found effects of time of day, day of the week, and season in the affective content of twitter messages. These studies suggest the importance of controlling for time of day when investigating the role of sleep in socio-emotional interactions.

**Inter-individual vulnerability in sleep & emotion**

*Sleep loss & emotion*

Individuals vary in their response to sleep loss, and in how different types of measures are affected [130]. These factors could be somewhat dissociable [131], suggesting that perceived impairments may not correlate with objective performance deficits, and the rate of sleep loss could also affect this [132]. The dose-response effects of sleep loss are also important to consider, and the effects of different kinds and durations of sleep loss. Individual differences in vulnerability to sleep loss seem important to investigate in conjunction with socio-emotional tasks, as this could contribute towards the effects of sleep loss on functioning. Baseline cognitive abilities, such as working memory, could also mediate the effects of sleep loss [21]. In addition, individuals also vary in aspects of emotion [62, 66], and social behavior is similarly complex [102]. In particular, trait anxiety has been reported to magnify the emotion effects of sleep disruption [22]. As individual differences related to the effects of sleep loss interact with tasks to affect performance, a detailed understanding of these relationships would be useful in order to predict the effects of sleep loss.

**CONCLUSIONS**

Sleep loss affects socio-emotional functioning in several ways. Emotional reactivity to emotional stimuli appears to be enhanced with sleep deprivation, with results most obvious in neuro-imaging studies. Tasks of behavioural inhibition are also sensitive to sleep deprivation. Sleep loss impairs social functioning, with results most apparent in measures of subjective emotional intelligence, and with some tasks of emotional face recognition. Emotional expressivity also seems to be impaired with sleep loss, and this has clear implications for social functioning. In general, the relationships between sleep,

emotion, and social functioning are complex, and the specific outcome measures (e.g. subjective/objective, behavioral, physiological, brain) could also affect reported results. Future studies should include multiple measures of emotion, and consider the inter-relationships between tasks, stimuli and measures. Consideration of the social context, and individual differences in emotion, social functioning, and sleep are also important. In addition, the role of (recovery) sleep, sleep stages, and circadian processes require clarification. As sleep affects socio-emotional functioning, and is associated with psychopathology, understanding the links of socio-emotional functioning and task performance with sleep is an important avenue of future research.

**Practice points**

- Sleep deprivation increases emotional reactivity, which is most apparent with fMRI results.
- Sleep deprivation impairs social functioning, measured by emotional expressivity parameters, and behavioral performance with emotional faces.
- Sleep-related daytime functioning, emotion, and social interactions are interlinked.
- Emotional tasks comprise different component processes, and multiple measures of performance are optimal.
- The social context of emotion tasks is as important as the emotional context.

**Research agenda**

- Include multiple measures of emotional responding, across domains.
- Consider the effects of the social context of experimental studies.
- Compare results of tasks measuring different components of socio-emotional functioning.
- Clarify the role of sleep stages, especially REM sleep, in emotional phenomenology.
- Investigate the effects of the circadian system in socio-emotional functioning.
- Assess the role of individual differences in sleep, emotion, and social functioning, in task performance.

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Table 1. Working definitions of key terms

| **Key terms** | **Definition** |
|---|---|
| Affective states, emotional states | "A conscious emotional feeling, with associated autonomic, neuroendocrine, and somatomotor responses" (Phillips et al., 2003). |
| Affective instability | "Rapid oscillations of intense affect, with a difficulty in regulating these oscillations or their behavioral consequences" (Marwaha et al., 2013). |
| Emotional blunting; decreased emotional reactivity/lability | Stable and slowly changing emotions due to hypo-reactivity to emotional stimuli. |
| Emotion perception | The perceptual processing of emotional stimuli. |
| Emotion regulation | The modification of an affective response by the recruitment of cognitive processes. |
| Emotional reactivity/lability (increased) | "Unstable and rapidly changing emotions due to hyper-reactivity to emotional stimuli" (Fountoulakis, 2010). |
| Socio-emotional stimuli | Emotional faces, voices, or images. |

Table 2. Summary of papers included within the review. Abbreviations: cardiac vagal tone (CVT), electrocardiogram (ECG), electromyogram (EMG), emotional quotient inventory (EQ-i), event related potentials (ERPs), functional magnetic resonance imaging (fMRI), high emotional reactivity (HER), low emotional reactivity (LER), polysomnography (PSG), Pittsburgh sleep quality index (PSQI), rapid eye movement sleep (REM sleep), rapid eye movement deprivation (REM-D), skin conductance response (SCR).

| | Author | Subjects | Design | Task | Stimuli | Measures | Result |
|---|---|---|---|---|---|---|---|
| 1. | Baglioni et al. (2014) | 22 insomnia disorder, 38 healthy good sleepers. | Between-subjects. | Emotional images were shown in five blocks, repeated twice. Assessed habituation. | Emotional images.<br><br>10 neutral with low arousal levels.<br><br>10 negative stimuli with moderate arousal levels.<br><br>10 negative stimuli with high arousal levels.<br><br>10 insomnia-related negative stimuli with moderate arousal levels.<br><br>40 neutral stimuli with low arousal levels. | fMRI results.<br><br>Recognition task. | Significant interactions of group and contrast (first presentation).<br><br>Healthy good sleepers showed increased amygdala activation to negative stimuli versus neutral stimuli with similar arousal levels. There was no such difference in insomnia patients.<br><br>Insomnia patients responded with increased activation to insomnia related stimuli compared to non-insomnia related stimuli. Healthy good sleepers showed the opposite pattern.<br><br>Healthy good sleepers showed similar amygdala activation to the first and second presentations of neutral moderate, negative moderate, and sleep negative images.<br><br>Insomnia patients displayed increased amygdala activation to the second presentation of neutral moderate |

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| | | | | | | | images. Conversely, they showed decrease activation with regard to negative moderate and sleep negative.<br><br>Healthy good sleepers also responded with increased amygdala activation towards negative stimuli compared to neutral, with no such effects in insomnia disorder. |
| 2. | Cote et al. (2014) | 49 healthy subjects. | Between-subjects. 24 subjects were sleep deprived. | Emotion face categorization. | Faces showing angry, sad, happy and fear, at different intensity levels (100%, 50%, 40% and 30%). | Behavioral; accuracy and reaction times. N170 and P1 ERP responses were analyzed. | Sleep deprived participants were less accurate towards sad faces and slower with the full expressions.<br><br>Sleep deprived subjects were less accurate with morphed sad faces, and slower with morphed happy, sad, and angry faces.<br><br>Sleep deprived subjects also had smaller P1 amplitudes and a larger N170 amplitude on the full face task. With morphed faces, sleep deprived subjects had a smaller P1 amplitude at 50% intensity, and main effects of sleep deprivation on N170 amplitude, with a larger amplitude in this group.<br>There was also a significant three-way interaction on the N170. |
| 3. | Kyle et al. (2014) | 16 psychophysiol | Between-subjects. | Emotion face | Faces showing | Behavioral; accuracy and | Lowered intensity ratings of sadness and |

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| | | ogical insomnia subjects; 15 controls. | | categorization and intensity judgments. | anger, fear, happy and sad expressions. | intensity judgments. | fear in insomnia. |
| 4. | DelVentura et al. (2014) | 12 insomnia subjects; 13 controls. | Between-subjects. | Emotional images were shown, with intermittent startle probes or pain induction, followed by emotional ratings. | Emotional images depicting mutilation, neutral, and erotica. | Behavioral ratings, and physiological measures. | Insomnia subjects rated mutilation images as less unpleasant, and erotica images as less pleasant. Pain ratings were not modulated by image in insomnia. Strength of the relationship between NFR and pain was weaker in insomnia. |
| 5. | Killgore, (2013) | 65 healthy adults. | Between-subjects. | Emotional intelligence task and questionnaire.<br><br>Sleep assessed via previous night's sleep duration. | Bar-On emotional intelligence inventory; Mayer-Salovey-Caruso intelligence test. | fMRI and subjective and objective emotional intelligence. | Less sleep was linked to lower subjective emotional intelligence. Sleep duration correlated negatively with prefrontal-amygdala connectivity. |
| 6. | Weber et al. (2013) | 55 healthy adults. | Between-subjects. Sleep assessed via habitual "sleep credit". | Emotional intelligence questionnaire. | Bar-On Emotional Intelligence Inventory (EQ-i). | fMRI and subjective emotional intelligence. | Sleep credit was correlated with greater grey-matter volume in two areas. EQ-I scores correlated with grey matter volume of the left grus rectus and superior and medial orbito-frontal gyrus. Grey matter volume in this area correlated with the interpersonal subscale of the EQ-i. |
| 7. | Motomura et al. (2013) | 14 healthy men. | Within-subjects. Sleep restricted to | Presented with emotional faces | Fearful, happy, or neutral faces. | fMRI, with button response to confirm wakefulness. | Significantly greater amygdala activation to fearful faces with sleep deprivation in |

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| | | | four hours of time in bed, with bed times four hours later than normal. | under conscious and non-conscious viewing conditions. | | | the conscious condition. Significantly diminished amygdala – ventral anterior cingulate cortex connectivity with sleep deprivation, which also correlates with mood. |
| 8. | Goldstein et al. (2013) | 18 healthy adults. | Within-subjects. Sleep deprivation of one night. | Emotional anticipation task whereby subjects were presented with an anticipatory cue, followed by neutral, negative, or combination images, and response judgements. | Combination, negative and neutral images. | fMRI and behavioral (omitted trial and response times). | Sleep deprivation enhanced anticipatory brain activity. Sleep deprivation was linked to more omitted trials, but no effects on reaction times. |
| 9. | Schwarz et al. (2013) | 33 healthy subjects. | Within-subjects. | "Smile or "frown" to emotional images and faces. | Positive and negative scenes, and happy and angry faces. | Behavioral ratings (arousal and valence) and EMG responses. | No effects of sleep group on arousal and valence ratings. EMG responses were slower with sleep loss. |
| 10. | Prather, Bogdan and Hariri, (2013) | 299 participants. | Between-subjects. Sleep quality assessed via the PSQI. | Perceptual face-matching task. | Anger, fear, surprised and neutral faces. | fMRI. | Poor sleepers had a significant positive relationship between amygdala reactivity and measures of psychopathology, unlike good sleepers. |
| 11. | Sundelin et al. (2013) | 10 healthy adults were sleep deprived. | Within-subjects. Sleep deprivation period of 31 hours, preceded by a night of 5 | Images were rated on cues related to fatigue, including sadness, | Photographs were taken of healthy adults when rested and following sleep | 40 observers rated faces for cues relevant to fatigue. | Sleep deprived individuals were perceived to be more sad and fatigued, with more swollen eyes, hanging eyelids, redder eyes, darker circles under the |

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| | | | hours of sleep. | dark circles under the eyes, pale skin, tense lips, and fatigue. | deprivation. | | eyes, paler skin, more droopy corners of the mouth, and more wrinkles and fine lines around the mouth. |
| 12. | Rosales-Lagarde et al. (2012) | 20 healthy adults. 12 REM-deprived, 8 controls. | Between-subjects.<br><br>REM sleep deprivation (REM-D), controls were awakened from other sleep stages. | Emotional reactivity task involved respondin g to image presentati ons with a button response. | Emotional images of negative and positive valence. High emotional reactivity (HER) images and low emotional reactivity (LER) images were identified for each individual. | Behavioral responses (emotional reactivity and reaction times). | HER responses increased after REM-D, with no such effects in controls. Reaction times at second test were decreased in the REM-D group for LER responses. |
| 13. | Baran et al. (2012) | 106 healthy adults. | Between-subjects.<br><br>Four groups, with testing before and after sleep, before and after wakefulness, morning testing, and evening testing. | Encoding phase with emotional judgments (arousal and valence), followed by a surprise recognitio n phase with emotional judgments (arousal and valence). | Emotional images (negative and neutral). | Behavioral arousal and valence, and memory. | Sleep group were more accurate with negative and neutral images, and made less false alarms.<br><br>Higher valence ratings in the wake group than the sleep group, with ratings in the wake group becoming more neutral. Similar results were found with valence in the wake group, whose responses became more neutral. |
| 14. | Minkel et al. (2012) | 97 adult volunteers. Sleep was assessed via the PSQI. | Between-subjects. | Emotional regulation task, whereby emotional images are | Neutral and negative images. | fMRI and behavioral (emotional reactions, neutral-negative). | Higher PSQI scores, and sleep medication use, were associated with less medial prefrontal cortex activity. |

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| | | | | presented, with subjects cued to look at the stimulus, or decrease their emotional response, followed by ratings. | | | |
| 15. | Gujar et al. (2011) | 36 healthy subjects. | Between subjects. | Subjects were allocated to a nap/no nap group, and completed an emotion face task twice. | Emotion faces of angry, fear, happy and sad were morphed with neutral to create an emotional range. | PSG and behavioral intensity ratings. | In the no-nap group, anger ratings were significantly increased at the second test, a result not found in the nap group. Fear ratings were also significantly reduced in the nap group, and increased in the no-nap group. Happy faces showed increased ratings at re-test in the nap group, with no significant change in the no-nap group. The effects with happy and fear in the nap group were driven by those who had achieved REM sleep. |
| 16. | Pace-Schott et al. (2011) | 46 volunteers. | Between subjects. | Subjects were allocated to a nap/no nap group, with the emotion task repeated twice. | Emotional images (negative and neutral). | Behavioural (valence and arousal), ECG, EMG, SCR. | Significant effects of nap/wake with physiological measures ("frowning" EMG and SCR). |
| 17. | Van Der Helm et al. (2011) | 34 healthy adults. | Between subjects. | Participants rated the emotional intensity of images | Emotional images, of positive and negative valence and | fMRI and behavioral intensity ratings. | Amygdala reactivity decreased, and ventromedial prefrontal cortex activity increased |

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| | | | | presented before and after sleep and wakefulness. | low and high arousal. | | following sleep.<br><br>Amygdala activity increased, and ventromedial prefrontal cortex activity increased following an equivalent period of wakefulness.<br><br>Emotional intensity ratings decreased in the sleep group and increased in the wake group. The extent of reduced prefrontal gamma during REM significantly predicted this effect. |
| 18. | Anderson and Platten, (2011) | 32 good sleepers, 16 per group. | Between-subjects. 36 hours of sleep deprivation. | Emotional Go/NoGo task. | Neutral or emotional (positive or negative) words. | Behavioral; hit rate and response times. | Faster incorrect responses and increased failure to inhibit a response. |
| 19. | McGlinchey et al. (2011) | 55 healthy participants, 17 adults. | Within-subjects. Sleep period the previous night of a maximum 2 hours. | Speak freely interview. | N/A | Computerized and human rater (eight raters) analysis of expressed emotion, computerized acoustic properties. | Increased negative expressed emotion, and alterations in vocal properties. |
| 20. | Minkel et al. (2011) | 23 subjects. 15 subjects were sleep deprived; 8 controls. | Between-subjects. Sleep deprivation period of one night. | Emotion-inducing films were shown, with responses recorded. | Movie clips to induce sadness and amusement. | Expressed emotion, facial movement analyzed via the FACES scoring system (two raters). | Sleep deprivation was linked to fewer facial movements to both types of movies. |
| 21. | Gujar et al. (2011) | 14 sleep deprived, 13 controls. | Between-subjects. Around 32 hours of sleep deprivation. | Viewing of increasingly pleasant images. | Emotional images raging from neutral (neutral valence, low arousal) to increasingly positive (positive | Emotional classification (pleasant/neutral).<br><br>fMRI and behavioral response (pleasant/neutral). | With sleep deprivation, an increased activation e.g. in brain areas responsible for reward, and altered functional connectivity, and a greater tendency to categorize stimuli as |

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| | | | | | valence, high arousal). | | pleasant. |
| 22. | Tempesta et al. (2010) | 40 subjects; 20 per group. | Between-subjects. One night of total sleep deprivation. | Passive viewing followed by behavioral responses. | Neutral, pleasant, and unpleasant images. | Behavioral; arousal and valence judgments. | Increased unpleasant ratings of neutral stimuli following sleep deprivation. |
| 23. | Baglioni et al. (2010) | 18 good sleepers; 21 primary insomnia. | Between-subjects. | Passive viewing. | Neutral, negative, positive, sleep negative and sleep positive images. | Heart-rate, cardiac vagal tone, facial EMG, subjective valence and arousal ratings. | Insomnia subjects showed decreased sleep-positive tonic responses of the corrugator, unlike good sleepers. Insomnia subjects had enhanced CVT, and no differences in the valence ratings of sleep-negative and general negative stimuli; and rated all stimuli as more arousing. |
| 24. | Chuah et al. (2010) | 24 healthy subjects. | Within-subjects. 24 hours of sleep deprivation. | Delayed match-to-sample working memory task for faces, with emotional distracters. | Images were high arousal negative, low arousal neutral, or digitally scrambled versions. | Behavioral ratings and fMRI. | Sleep deprivation impaired working memory performance, but did not affect ratings of intensity or distractibility. Working memory decreases correlated with increased amygdala activation to distracters with sleep deprivation, and functional connectivity. |
| 25. | Van Der Helm et al. (2010) | 37 healthy subjects.<br><br>20 sleep deprived and 17 controls. | Between-subjects (total sleep deprivation vs. controls). | Intensity judgments of emotion faces. | Faces displaying anger, sad, and happiness morphed with neutral. | Behavioral intensity ratings. | Sleep deprived subjects made lower intensity ratings of happy and angry faces. |
| 26. | Kuriyama, Soshi, and Kim, (2010) | 28 healthy students.<br><br>14 sleep | Between-subjects. One night of sleep | Passive viewing (memory encoding). | Movies of safe driving and of a motor | Recognition accuracy (old-new) and fear rating, skin | Sleep deprivation diminished the fear rating of SAFE movies. Sleep deprivation |

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| | | deprived, 14 controls. | deprivation. | | vehicle accident. | conductance response (SCR). | diminished the SCR in all contexts to incorrectly identified stimuli. |
| 27. | Lara-Carrasco et al. (2009) | 35 healthy subjects.<br><br>17 REM deprived, 18 controls. | Between-subjects (REM sleep deprivation vs. controls). | Arousal and valence ratings of emotional images at night and in morning. | Emotional images, including neutral and negative images. | Behavioral ratings (valence and arousal) and PSG. | Emotional adaptation (arousal) scores were significantly lower in the in those subjects with a high REM %. No effects were found with neutral images or valence ratings. |
| 28. | Franzen et al. (2009) | 30 healthy volunteers. 15 subjects per group. | Between-subjects. One night of total sleep deprivation. | Passive viewing task. | Emotional images (neutral, positive and negative). | Behavioral ratings of valence and arousal and pupillography. | Sleep deprived subjects showed anticipatory reactivity to negative blocks, and larger pupil diameters to negative images. |
| 29. | Franzen et al. (2008) | 29 healthy adult volunteers. 15 subjects per group. Between-subjects. | One night of total sleep deprivation. | Objective and subjective measures of sleepiness and mood. | Positive, negative, and neutral images. | Self-reports, behavioral, and physiological measures. | Distinction of subjective and objective measures was less clear following sleep deprivation. |
| 30. | Huck et al. (2008) | 54 healthy subjects. | All subjects sleep deprived, up to 44 hours of sleep deprivation. Between-groups comparisons. 3 drug conditions and a placebo group. | Recognition of angry, sad, happy, surprised, fearful and disgusted faces. | Ekman 60 Faces test, the Emotion Hexagon Test. | Behavioral; accuracy. | Sleep deprivation impairs recognition of complex emotions, which all drugs improve. |
| 31. | Yoo et al. (2007) | 14 sleep deprived, 12 controls. | Between-subjects comparisons. Around 35 hours of sleep deprivation. | Viewing of increasingly aversive images. Emotion classification response | Emotional images, ranging from emotionally neutral to increasingly aversive. | fMRI and behavioral (unpleasant/neutral). | Sleep deprived subjects showed amygdala responses with impaired prefrontal connectivity. |

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| | | | | to verify wakefulness. | | | |
| 32. | Pallesen et al. (2004) | 36 cadets. | Within-subjects. Sleep deprivation period of 72 –120 hours. | Delayed match to sample task with faces, presented to visual half-fields. | 9 schematic facial expressions. | Behavioral; reaction times and accuracy. | Less accurate with sleep deprivation. Significant interaction of half field with state on reaction times. |
| 33. | Wagner, Fischer, and Born, (2002) | 24 healthy subjects. | Within subjects. | Emotional judgments were made before and after sleep which was taken early or late at night. | Aversive images. | Behavioral ratings (arousal and valence). | Old-new valence ratings were more positive after early sleep and more negative after late sleep. Old-new arousal ratings were greater after sleep than wakefulness. |
| 34. | Harrison and Horne, (1997) | 9 healthy subjects. | Within subjects.<br><br>One night of sleep deprivation (36 hours). | Word fluency task and short story oral reading. | N/A | 10 trained raters. | Decreased word count during sleep deprivation; small increase on control nights (trial 3).<br><br>Larger proportion of semantically-related words during the last two trials of sleep deprivation (trial 2 and 3).<br><br>Diminished number of nouns and adjectives during trial 3 of sleep deprivation.<br><br>Deterioration of intonation by day two of sleep deprivation, and sleep deprivation increased fatigue. |
| 35. | Dushenko and Sterman, (1984) | 10 healthy subjects. | Within subjects (sleep adaptation night and REM | Left and right hemisphere tasks were presented | 25 cartoon drawings of adult faces (extremely positive, mildly | Same/different judgments (accuracy and reaction times). | There was a significant improvement in performance in the night 2 to night 3 left hemisphere first |

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| | | | deprivation). | to subjects tachistoscopically. | positive, neutral, mildly negative, extremely negative).<br><br>80 abstract nouns. | | presentation of the facial stimuli.<br><br>The left hemisphere first presentation of faces was linked to higher accuracy than the right hemisphere first presentation. |

Table 3. Summary of relevant methods. Abbreviations: autonomic nervous system (ANS), electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), event related potentials (ERPs), functional magnetic resonance imaging (fMRI), positron emission tomography (PET), peripheral nervous system (PNS).

| **Measures** | **Processes** |
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| Behavioral tasks | Objective measures of task performance, with accuracy and reaction times indicators of underlying cognitive processes. |
| Neuro-imaging techniques | EEG and ERPs, fMRI and PET can be used to measure recruitment of brain areas and activity, and connectivity between them. |
| Observed behavior | Facial expressivity, generation of social cues, reactions to social cues, social interactions. |
| Questionnaires | Subjective emotional experiences, emotional regulation and intelligence, meta-emotion and meta-cognition, subjective social functioning. |
| Physiological responses | EMG, ECG measures derived from heart-rate, skin-conductance response, and measures of ANS/PNS activity. |

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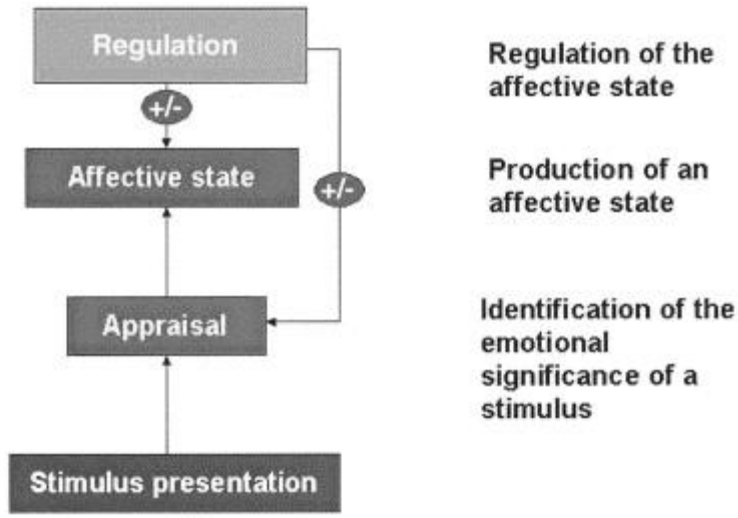

Figure 2. Systematic review procedure